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COLLABORATIVE RESEARCH AND DEVELOPMENT (CR&D)

Delivery Order 0064: Advanced Computational Dynamics Simulation of Protective Structures Research

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14. ABSTRACT
This research in support of the Air Force Research Laboratory Materials and Manufacturing Directorate was conducted at Wright-Patterson AFB, Ohio from 21 December 2006 through 1 February 2008. This task defined the effects of extreme dynamic loading on civil structures reinforced with advanced materials. Due to the nonlinear behavior of concrete masonry walls, the use of advanced simulation techniques provides advantages over experiments for full understanding of their structural responses under explosive loads. In this study, several finite element models were developed according to blast test conditions, and analyzed using LS-DYNA explicit code. Input sensitivity studies were conducted to investigate the variations of a wide range of parameters on wall deformations, damping coefficients, boundary conditions, and arching action. The effort has led to cost effective analysis techniques for use by structural engineers in designing membrane retrofit concrete masonry walls subjected to blast loads. This report summarizes the simulation methodologies, challenges, techniques, and comparison to full-scale dynamic tests for membrane retrofit concrete masonry walls.

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14. ABSTRACT (alternate)

Mitigation techniques are currently sought to ensure public safety in the event of intentional or accidental explosions. The use of concrete masonry walls in civilian and military buildings is one of the most common methods of construction. These walls, however, are vulnerable to impulse loads, and can result in collapse, fragmentation, and severe injury to occupants. Over the past several years, the Airbase Technologies Division of the Air Force Research Laboratory has investigated methods of retrofitting concrete masonry walls to better resist blast loads from external explosions. One method that has demonstrated to be very effective is the application of thin membranes of high elongation materials to the inside surface of the walls. Due to the nonlinear behavior of concrete masonry walls, the use of advanced simulation techniques provides certain advantages over experiments for full understanding of their structural responses under explosive loads. In the present study, several finite element models were developed according to blast test conditions, and analyzed using LS-DYNA explicit code. Input sensitivity studies were conducted to investigate the variations of a wide range of parameters on wall deformations, damping coefficients, boundary conditions, and arching action. The effort has led to cost effective analysis techniques for use by structural engineers in designing membrane retrofit concrete masonry walls subjected to blast loads. This report summarizes the simulation methodologies, challenges, techniques, and comparison to full-scale dynamic tests for membrane retrofit concrete masonry walls.

1.0 INTRODUCTION

Terrorists commonly target military and diplomatic facilities, as well as populated residential buildings, office buildings, and restaurants. Most casualties and injuries sustained from terrorist attacks are not caused by the pressure, heat, or container fragments resulting from a bomb detonation, but are typically blunt trauma and penetration injuries caused by the disintegration and fragmentation of walls, the shattering of windows, and by non-secured objects that are propelled at high velocities by the blast. Ensuring that the exterior walls of a building are able to withstand a blast without producing deadly fragments is a critical aspect of minimizing injuries to building occupants.

Over the past decade, the Air Force Research Laboratory (AFRL) has conducted research towards developing lightweight, expedient methods of retrofit-strengthening structures for blast loading. A recent focus has been on strengthening unreinforced, non-load bearing concrete masonry walls due to the frequency of use in common building construction that typically has a high density of occupants, and the susceptibility of these structures to deadly fragmentation under relatively low blast pressure. Although a wide range of potential reinforcement materials were investigated by AFRL engineers and other agencies involved in blast retrofit technology development, the most promising technology developed was the use of elastomeric polymers applied the building interior side of the masonry (Davidson et al. 2004, 2005; Knox et al. 2000). Seven blast tests were conducted that involved a total of twelve spray-on polymer reinforced masonry walls. The goal of these tests was to understand the failure mechanisms involved with polymer retrofit concrete masonry walls; the research has lead to the development of analytical models used to predict their capacity and collapse mechanism.

1.1 Arching

When a masonry wall is built between and in tight contact with supports that serve as restraints against outward movement, elongation of the tension face due to bending cannot occur without inducing a compressive force (Drysdale et al. 1994). Under lateral load, this induces in-plane compressive force results in arching, which increases the cracking load significantly. With increased loading, flexural cracking occurs at the supports and the midspan of the wall.

Several studies have been conducted to investigate the effects of arching on the failure mechanism of the unreinforced and reinforced masonry walls under different loading conditions. The earliest in-depth investigation of the arching action theory of unreinforced masonry walls was carried out by McDowell et al. (1956). It represented a rather radical departure from the resistance of lateral forces usually assumed for this type of construction. The theory was used to obtain the static load-deflection curves for masonry beams of solid cross section. The results showed significant improvement in the resistance of these beams to lateral uniform loads. McDowell et al. (1956) noted that, under certain conditions, masonry walls withstood much larger loads than those predicted on the basis of conventional bending analysis. The additional strength was developed when the walls were butted up against supports that were rigid. This type of wall exhibited three to six times the load-carrying capacity of simply supported walls. McDowell et al. (1956) ran a series of static tests on different sizes of solid, unreinforced masonry beams exposed to lateral uniform loads and compared the results to those derived from their proposed theory.

Gabrielsen et al. (1973 and 1975) performed extensive blast tests on arched unreinforced masonry walls. The tests showed that arched walls are considerably stronger, by as much as four to five times, than nonarched walls. Gabrielsen et al. (1975) also shock-tunnel tested gapped arched walls and concluded that they were significantly weaker than the arched walls without gap. Drysdale et al. (1994) used the same approach as that employed by McDowell et al. (1956) to develop a simpler equation for the arching resistance of unreinforced masonry walls under lateral loads. The approach considered arching for one-way action walls confined between rigid boundaries at their top and bottom interfaces. More recently, Dinan et al. (2003) examined the arching resistance of polymer retrofit concrete masonry walls using the method outlined by Drysdale et al. and the Wall Analysis Code (WAC) (Slawson 1995) to arrive at resistance functions that matched well with full-scale test data. While the arching has proved to increase the resistance of the masonry walls in these tests, it is not fully understood how arching forces benefit the masonry wall structure's deformation under explosive loads.

1.2 Membrane Catcher System

The membrane catcher system in unreinforced concrete masonry walls is designed to catch the fragments caused by blast pressure. The fragments can travel into the occupied space at high speed and cause injury and even death. A typical unreinforced concrete masonry wall catcher system may consist of the CMU wall and the membrane catcher material on the inside face of the wall. The membrane catcher system may be made of metal such as thin steel or aluminum sheets, and is attached to the floor and to roof of the room associated with the wall using sound structural interfaces, but it not attached to the masonry wall.

Slawson et al. (1999) described the use of a typical membrane catcher system in which anchored fabrics were used to retrofit concrete masonry unit walls exposed to blast pressure. Single-degree-of-freedom (SDOF) and finite element models were used in an attempt to simulate test results. The anchored fabric retrofit technique was not intended to strengthen the masonry walls. Its purpose was to catch hazardous debris caused by the disintegration of the wall (Slawson et al. 1999). Anchored to the roof and floor slabs of a structure on the inside face of a wall, the fabric acts like a net that catches broken pieces of the wall and reduces the threat to occupants. Two commercially available geofabrics were used during explosive tests. The geofabrics were successful in preventing debris from entering the interior of the test structure. A total of six wall panel models were generated using the WAC SDOF software and the DYNA-3D finite element software (Slawson et al. 1999). Each wall panel model was given a width of 120 inches and a height of 104 inches. For both the WAC and DYNA-3D models, there was one control wall and two walls that were retrofitted with the anchored fabric. The membrane resistance of the anchored fabric was added to the resistance function of the WAC-generated wall panels to account for the retrofit. Results from the WAC and DYNA-3D models were compared to the data collected from the explosive tests, which did not agree well. The results indicated that the maximum displacements for the retrofitted walls were being overestimated. It was suggested that additional experimental data would be required to fully validate the computation procedures (Slawson et al. 1999).

Thornburg (2004) reports a test at Tyndall AFB in which two CMU walls were exposed to blast loads. One wall incorporated the membrane polymer catcher system, while polymer was sprayed directly on the other unreinforced concrete masonry wall. The walls were identical except for the application of the polymer. The wall with the membrane polymer catcher system

sheared at the top connection and collapsed during the test, but prevented debris from entering the structure.

1.3 Computational Modeling of Masonry Walls and Retrofit Measures

The large expense associated with performing explosive tests necessitated a reliance on computational techniques to investigate the effectiveness of retrofit materials. Connell (2002) developed and used advanced computer models to evaluate the benefits of retrofitting masonry walls with elastomeric polymers subjected to blast loads. While the results of the AFRL tests clearly demonstrated that the spray-on polymer material was effective in reducing both wall deflection and fragmentation, Connell suggested that WAC was not suitable for the addition of low-stiffness polymers to masonry walls, and pointed out that the behavior of such a wall during a blast event is highly dynamic and nonlinear in nature. His attempts to use the "user defined," "unreinforced masonry walls (URM)," and "cavity wall" options in WAC to incorporate the effectiveness of retrofit polymers remained unsatisfactory.

Connell then developed high-fidelity FE models using the LS-DYNA code to investigate the effectiveness of low-stiffness polymers on masonry walls. The eroding element feature was used to simulate the failure patterns seen in the explosive tests. However, numerical values for wall response were not accurate, due to difficulties in implementing the proper failure criterion for the material models. The one-way action strip model failed in shear near the supports, while the actual walls failed in bending at midpoint. Connell concluded that the difference in the failure modes was due to problems associated with the material models selected. Connell suggested that the constitutive model was the key to better model correlation with test results.

A number of available material models in LS-DYNA were examined to arrive at the one most suitable for the behavior of concrete masonry walls during blast (Moradi 2003). The focus was on a single CMU, and four constitutive models in LS-DYNA code were used in the finite element analysis in the present study, including MAT_SOIL_AND_FOAM (MAT_5), MAT_BRITTLE_DAMAGE (MAT_96), MAT_PSEUDO_TENSOR (MAT_16), and MAT_WINFRITH_CONCRETE (MAT_84). Overall, the MAT_SOIL_AND_FOAM constitutive model produced better prediction than the other three. This model was also the simplest of the four and was developed for cases of plane soils, foams, and concrete. This closely matched the make-up of a common CMU composed of plain concrete material exhibiting simple fracture modes. The other three constitutive models were developed for more complex concrete and reinforced concrete structures. The MAT_PSEUDO_TENSOR model was used for buried, steel-reinforced concrete structures subjected to impulsive loads. Moradi (2003) therefore recommended the use of MAT_SOIL_AND_FOAM for analytical investigations of the effects of blast loads on CMU walls.

Sudame (2004) developed a finite element model based on blast tests conducted at AFRL. Although Sudame's analyses were comprehensive, it was unable to distinguish between the arching case and the case without arching. The changes in boundary conditions representing no gap (arching) and the presence of a gap (no arching) did not result in significant differences in the final displacement response of the wall. This issue required attention and a final resolution in light of the evidence by test and other analytical methods that arching was a significant issue in behavior of CMU walls.

1.4 Purpose

The objectives of this investigation were to: 1) Develop finite element models of membrane retrofit masonry walls with selection of a suitable constitutive model, and validate the model with existing test results; 2) Provide insight into the distribution of strain over the response time interval and thus to better understand failure mechanisms; 3) Compliment data taken during a minimum number of blast tests with parametric analyses involving a wide range of variables; and 4) Investigate and adopt modeling techniques that could be used to explore the feasibility of other masonry retrofit concepts prior to blast testing. This report discusses the modeling approaches used and summarizes key conclusions gained for membrane retrofit concrete masonry walls.

2.0 FULL-SCALE DYNAMIC TESTS

In 1999, AFRL researchers began looking for retrofit techniques to increase the blast resistance of common exterior walls. One of the goals was to develop a retrofit technique that did not have difficult application processes and the high expense of commonly used methods for strengthening walls, such as increasing the mass with reinforced concrete. The need arose for a “lighter weight solution” that would “introduce ductility and resilience into building walls” (Knox et al. 2000). An polyurea base elastomeric polymer was chosen for use as a retrofit material based upon the results of material testing. The material was selected based on its strength, flammability, and cost. The application method for this material was a relatively straightforward spray-on process, as shown in Fig. 2.

Figure 2. Application of Spray-on Polymer

Proof-of-concept tests were performed using blast-loaded masonry walls and lightweight structures retrofitted with the polymer material. The material was easily sprayed onto the interior and exterior wall surfaces while control over the application thickness was monitored. The proof-of-concept tests showed that the masonry and the lightweight structure walls experienced large deflections without breaching, and that no debris entered the interior of the test structures. The lightweight structure used in the proof-of-concept tests stayed intact, but the structure experienced severe ceiling crushing, which needed to be mitigated.

A picture of a typical masonry test wall is shown in Fig. 3. Each test wall is 12 feet tall by 8 feet wide and made of 8-inch CMU block. The system was subjected to the blast loads described herein. A rapid variation of stresses and strains results in the wall components. To effectively capture this phenomenon, the selection of appropriate material models is critical.

Figure 3. Test Wall Setup.

The setup used unreinforced masonry walls measuring 7 feet 4 inches in width and 12 feet in height. The density of masonry concrete is approximately 0.07 pound/inch^3, which results in a weight of each block of approximately 32 pounds. The walls were constructed in reusable reaction structures. 3-inch x 4-inch x 0.25-inch steel angles were placed at top and bottom of the test wall to restrain lateral movement. The typical CMUs used in the tests were standard hollow concrete blocks weighing 32 pounds. The dimensions of the blocks were 7.625-inch x 7.625-inch x 15.625-inch. The outer edges of the block were 1.25-inch thick, and the center web was 1-inch thick. The blocks have a nominal compressive strength of 2000 psi. Mortar joints of approximately 3/8-inch thickness with type-N mortar separated the blocks (Connell 2002; Thornburg 2004).

The AFRL research team continued the development and testing of the polymer retrofit technique by shifting their focus to the retrofit of CMU walls. An overview and discussion of the CMU wall tests carried out by the AFRL, at Tyndall AFB, is presented by Connell (2002). Connell reported that three masonry wall tests were conducted by AFRL during the early part of 2001 with the spray-on polymer retrofit polyurea. Two tests used a retrofit spray-on wall versus an unreinforced CMU wall without retrofit. The first test showed that the unreinforced CMU wall collapsed unlike the retrofit sprayed-on wall, which stayed in place with some damage (Fig. 4).

Before **After**

Figure 4. Test Set-Up and Results.

3.0 FINITE ELEMENT MODEL DEVELOPMENT

Based on the blast tests conducted by AFRL, Sudame (2004) developed a detailed model of a one-way flexure, single-CMU-width masonry wall and used it to investigate wall behavior using the constitutive models suggested by Moradi (2003). The overall dimensions and support conditions reflected explosive tests conducted at AFRL (Fig. 5). The masonry wall structures involved in the AFRL tests had six key components that had to be accurately included in the model development: the CMU, mortar joint interfaces, polymer retrofit (material behavior and interface with masonry), and roof and floor boundaries.

The spray-on polymers were primarily comprised of polyurea blends. Table 1 provides the key mechanical characteristics of the material considered (Davidson et al. 2004). The stress-strain curve was obtained from static uniaxial tension tests conducted by AFRL (Fig. 6), where the material exhibited a discernible yield point and an elongation capacity of approximately 80% (Knox et al. 2000).

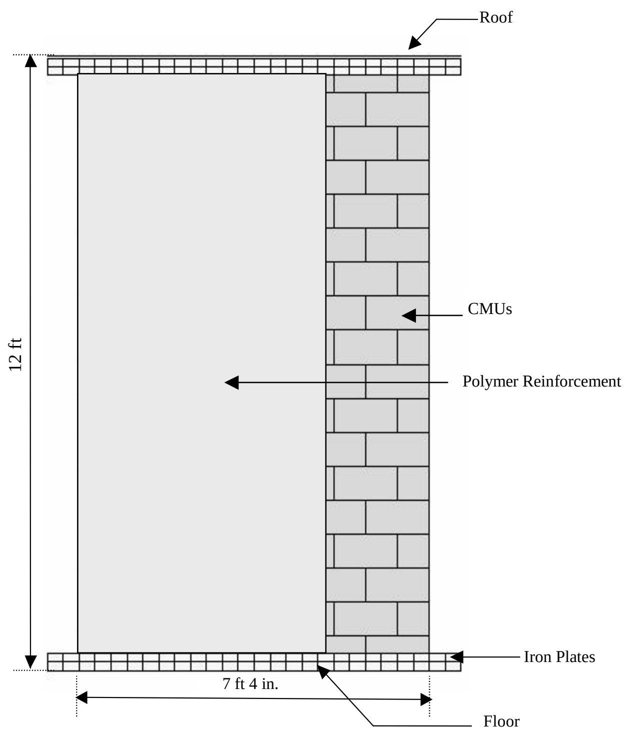


Figure 5. Schematic of wall setup.

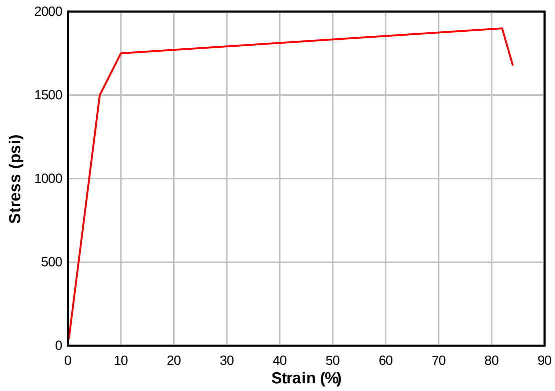


Figure 6. Static Stress-Strain Curve for the Spray-On Polymer

Sudame's baseline model consisted of 18 hollow concrete blocks connected by a mortar interface. Mortar was simulated only over the flanges of the concrete blocks.

Table 1: Properties of the polymer retrofits

Property	Value
Modulus of Elasticity	34000 psi
Tangent Modulus	3400 psi
Elongation at Rupture	89%
Stress at Rupture	2011 psi
Maximum Tensile Strength	2039 psi
Density	90 pound/ft^3
Poisson's Ratio	0.4
Shear Modulus	11620 psi

The CMUs were supported by the rigid floor boundaries. A gap was placed between the top most block and the roof boundary with the thickness of one mortar joint. This provided room for the rotation of the top block.

A boundary 1-inch wide extending through the width of one block on the backside at the top and bottom provided a restraint against lateral movement of the wall. The side subjected to the blast load is referred to as the "front". The polymer coating was simulated only on the rear of the block. The distance between the boundaries and the block was equal to the thickness of the polymer. Fig. 7 illustrates the overall model setup. Various contact definitions and parameters were selected as follows:

a) The MPP version of LS-DYNA does not support the CONTACT_ TIEBREAK_SURFACE_TO_SURFACE contact type. Interfaces between blocks and mortar layers were, therefore, modeled by the TIEBREAK_NODE_ TO_SURFACE contact type. Node sets were made slaves, and the segment sets were made master in each block-mortar interface contact. Failure criteria was dictated by NFLS equal to 100 psi and shear SFLS equaling 250 psi (Drysdale et al. 1994).

b) The TIEBREAK_NODE_TO_SURFACE contact definition was used for contact between the polymer and the blocks. Polymer nodes were made to act as slaves and the block segment sets act as master.

The spray-on polymer approach results in a very strong bond between the concrete and the polymer (Thornburg 2004), so a value of 1 was used for the static coefficient of friction. The value of dynamic friction chosen was 0.8, which is the friction between concrete and rubber. Tension tests on polymer-reinforced concrete block resulted in concrete spalling without separation of polymer from concrete (Dinan et al. 2003); therefore, a 150-psi tensile limit was used as the normal failure force for the bond between polymer and concrete, and a shear failure force of 1000 psi was used for contact definition.

The rigid top and bottom boundaries resist the lateral translation of the wall, which results in high shear forces at the top-most and bottom-most mortar joint interfaces. Relative motion occurs between the lowermost block and the block above it due to less freedom for rotation. A similar phenomenon is observed near the upper block (Fig. 8b); however, the space between the top block and roof boundary allows the upper block to rotate. Less shear is observed at the top mortar joint as compared to the shear at the bottom mortar joint. The amount of rotation that occurs depends on the presence of rigid boundaries on the front side and their width. Absence of the boundaries results in more rotation and less shear.

A noticeable flexural response then occurs. The blocks near the midpoint separate in tension, and the wall continues to deflect until its movement is resisted by the polymer reinforcement (Fig. 8c). At this point, the polymer is subjected to tension. If the polymer has low rupture strain, it fails in tension, allowing further movement of the wall. If the polymer does not reach its tension limit, it rebounds slightly.

Several finite element models were developed and input sensitivity studies were conducted to investigate the effects of variations in polymer thickness, damping and presence of arching force on the wall deformation and failure mechanisms under experimental blast loads (Sudame 2004).

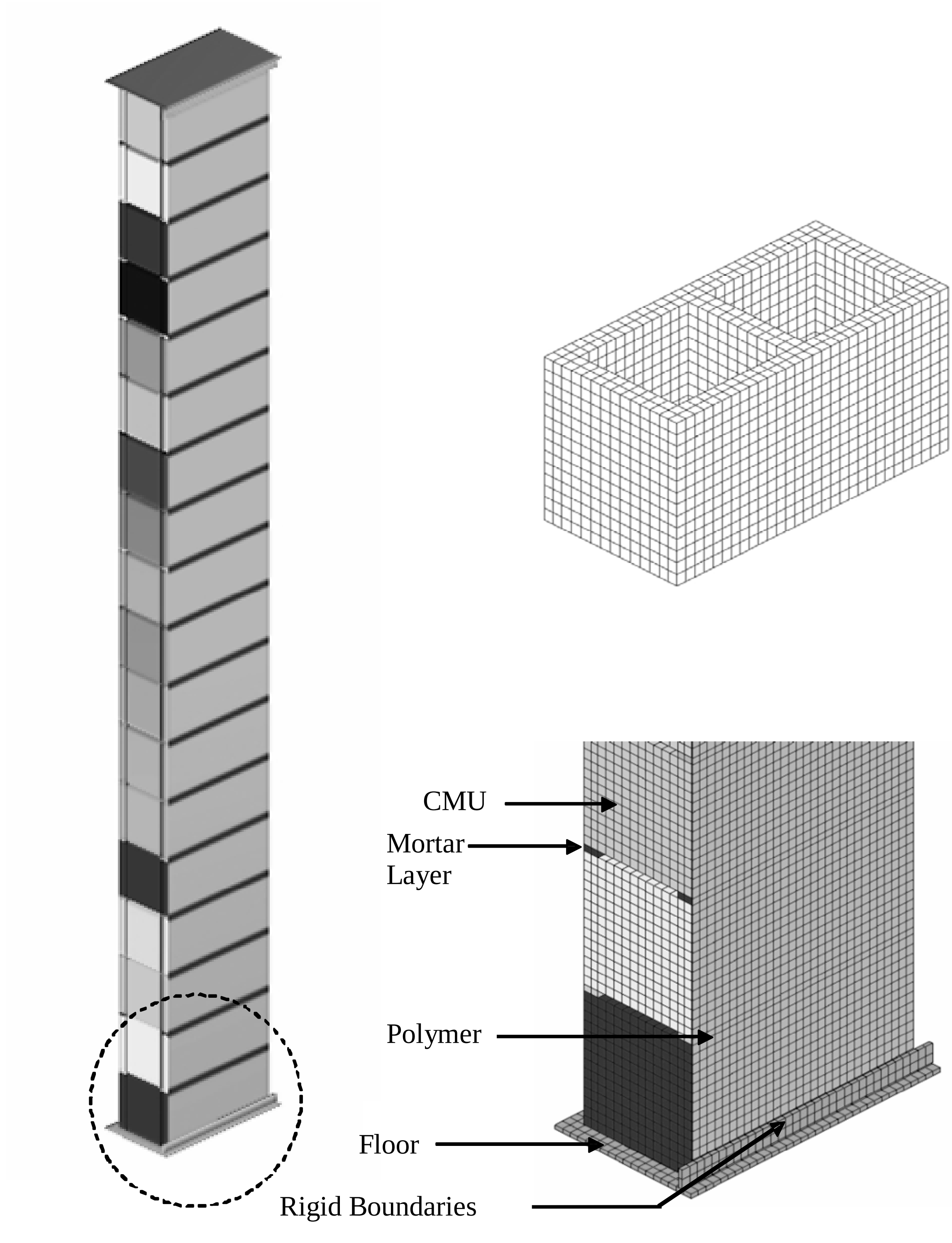
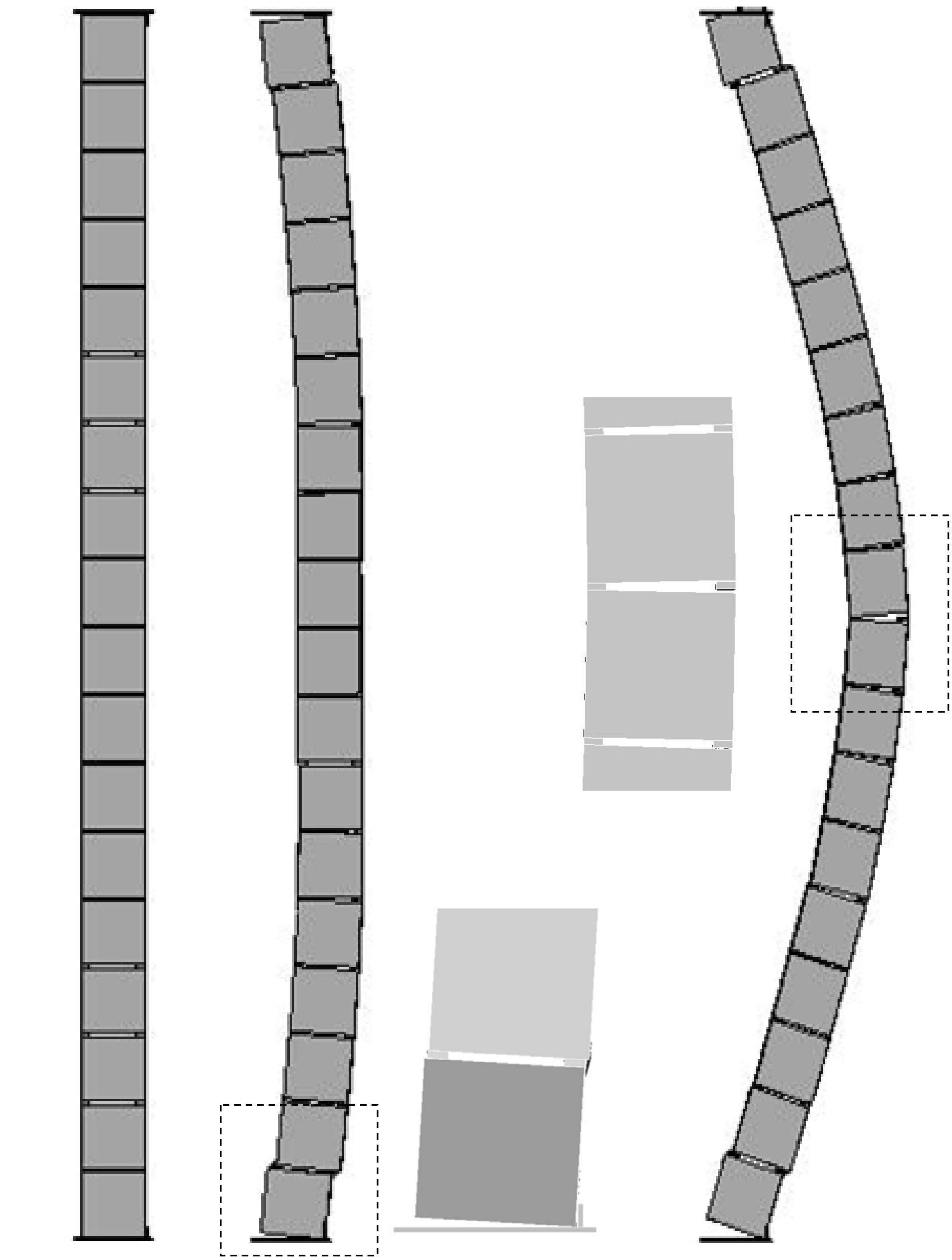


Figure 7. Baseline Model Setup.



(a) Initial Stage (b) Shear at Supports (c) Bending at Center

Figure 8. General Wall Behavior.

4.0 FINITE ELEMENT ANALYSIS

The FE models were analyzed for seven wall tests of height of 144 inches. The impact of the corresponding changes in boundary conditions regarding the lack of a gap (arching) and the presence of one (no arching) were investigated for significant differences in the final displacement response of the wall. The left picture in Fig. 9 shows no gaps between the base of the wall and support, and the right picture in the same figure shows a 0.5-inch gap between the base of wall and the support. At the top interface of the wall, the same boundary conditions are repeated.

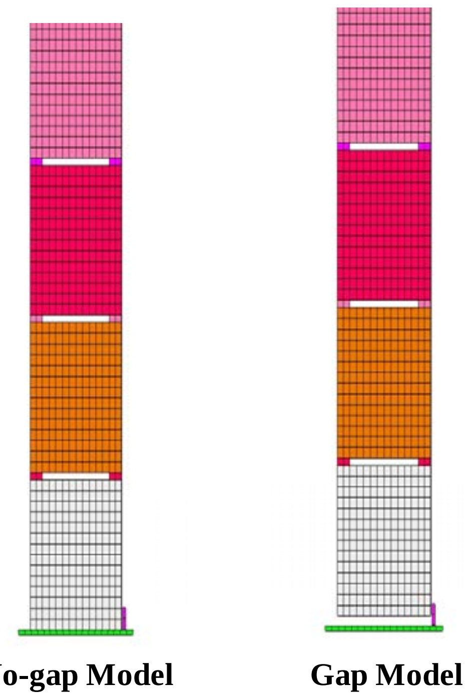


Figure 9. FE Model With and Without Gap.

As mentioned earlier, Sudame (2004) was unable to distinguish between the arching case and the case without arching. The corresponding changes in boundary conditions regarding the lack of a gap (arching) and the presence of one (no arching) did not result in significant differences in the final displacement response of the wall. To further investigate this issue, another constitutive model was selected for analysis. The MAT_BRITTLE_DAMAGE model is anisotropic and designed primarily for concrete and steel reinforced concrete, though it can be applied to a wide variety of brittle materials (LS-DYNA 1999). It admits progressive degradation of tensile and shear strengths across smeared cracks that are initiated under tensile loadings and compressive failure can be disabled if not desired. Compressive failure is governed by J2 flow correction that can be disabled if not desired. For concrete, an initial tensile strength is specified by the user. Once this stress is reached at a point in the body, a smeared crack is initiated there with a normal that is co-linear with the first principal direction. As the loading progresses the allowed tensile traction normal to the crack plane is progressively degraded to a small machine dependent constant. The degradation is implemented by reducing the material's modulus normal to the smeared crack plane according to a maximum dissipation law that incorporates exponential softening. The crack field intensity is output in the equivalent plastic strain field in a normalized fashion. When normalized value reaches unity, it means that the

material's strength has reached 2% of its original value in the normal and parallel directions to the smeared crack. The initial shear traction may be transmitted across a smeared plane. The shear degradation is coupled to the tensile degradation through the internal variable, which measures the intensity of the crack field. The shear degradation is accounted for by reducing the material's shear stiffness parallel to the smeared crack plane.

The material card used in the analysis for MAT_BRITTLE_DAMAGE is listed below with corresponding tabulated values. Values that could be readily calculated using available data in the literature are shown accordingly. Values for the fracture toughness, shear retention, and viscosity were estimated using recommendations provided in the LS-DYNA user's manuals.

```
*MAT_BRITTLE_DAMAGE

$      mid        ro         e        pr    tlimit    slimit    ftough    sreten

         1  0.0062224 2000000.0      0.15     200.0     100.0      0.80     0.030

$     visc    fra_rf      e_rf     ys_rf     kh_rf     fs_rf      sigy

     104.0       0.0       0.0       0.0       0.0       0.0    2000.0
```

Where:

mid: Material identification number

ro: Mass density

e: Elastic modulus

pr: Poisson's ratio

tlimit: Tensile strength

slimit: Shear strength

ftough: Fracture toughness

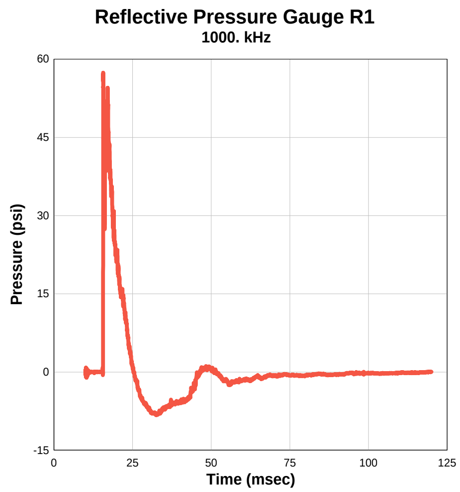
sreten: Shear retention

visc: Viscosity

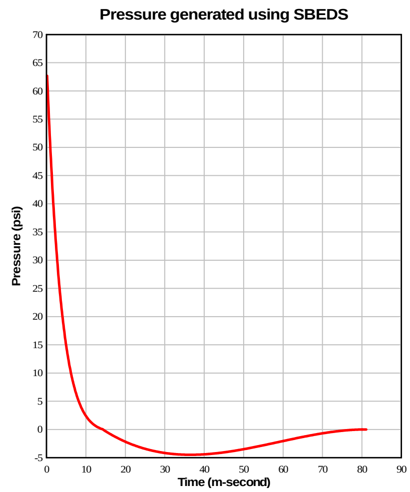
fra_rf….sigy: Values related to reinforcement

Damping coefficients in the finite element model were varied to quantify its effect on wall deformation. Damping values of 1% to 5% were used in the analysis, and no significant variation in the system performance was observed. The thickness of the polymer retrofit was adjusted according to each test as shown in Table 2.

The constitutive model for the MAT_BRITTLE_DAMAGE was incorporated in the finite element model of the wall, and analyses were performed using blast load pressure curves generated with SBEDS program. It is important to note that the pressure curve generated using SBEDS or other available methods (Fig. 10, right) is at best an approximation and does not completely match the measured pressure curve from the actual test (Fig. 10, left).



Test Pressure vs Time



Analysis Pressure vs Time

Figure10. Blast Load for Test 1.

5.0 RESULTS

The analysis results showed distinct differences in wall deformations between the arching cases and those without arching. Test 1 simulation (Figure 11) indicated significant arching forces for the no-gap boundary conditions, and zero arching forces for the boundary condition with a gap. The results also showed significant differences in the overall response of the wall between the arching and no-arching case. A maximum displacement of 6.9 inches was found for the arching case as compared to wall failure for the no-arching case (Fig. 12). In the case, the finite element run terminated due to excessive displacements, as evident by the discontinuity at the peak of the blue curve in Fig. 12. The results show a crack developing at the midpoint of the wall on the tension face and opening wider as the wall deflects (Fig. 13). In the arching case, the crack continues to open but the masonry elements remain in contact at the mid-point of the wall on the compression face (Fig. 14). The membrane retrofit remains intact for the most part in the arching case, but completely fails for the no-arching case. The maximum displacement results of the finite element analysis are within 4.2% of the test results at 7.2 inches for Test 1.

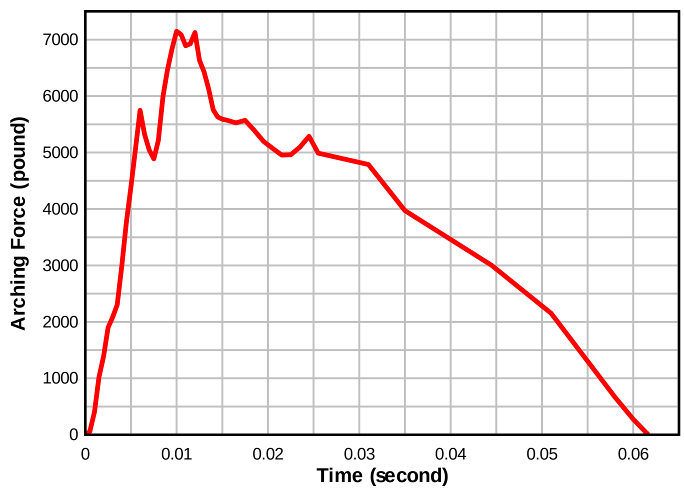


Figure 11. Arching Forces for Test 1.

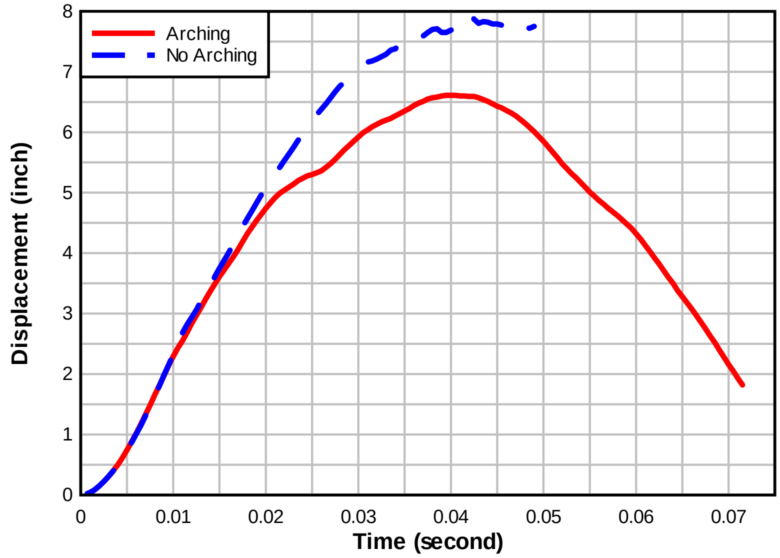
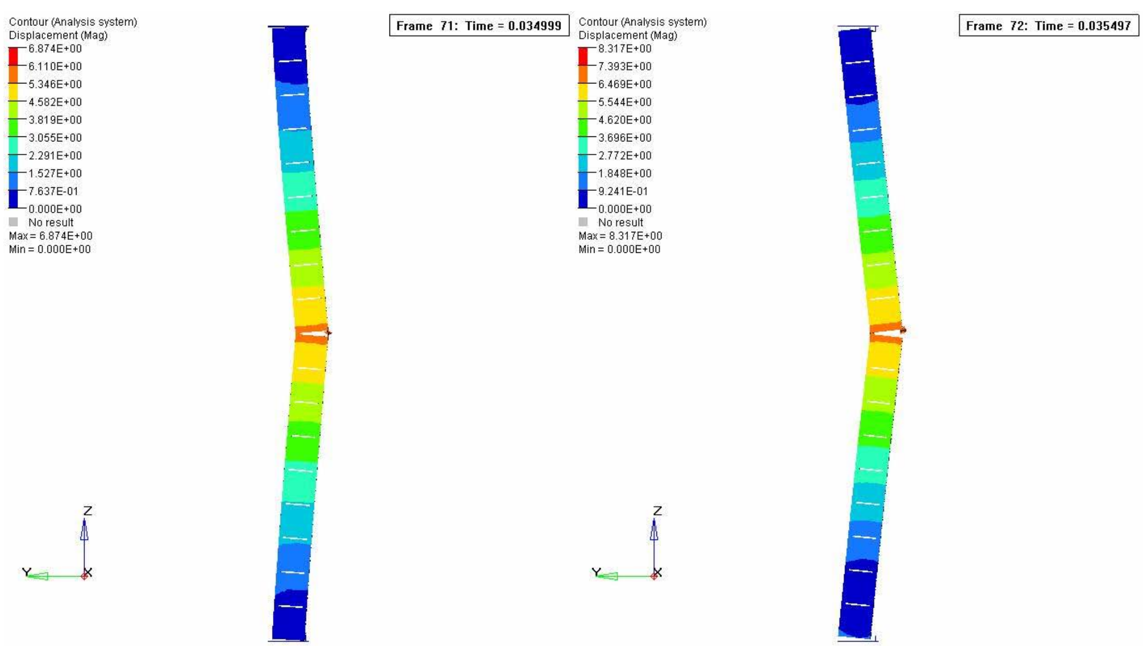
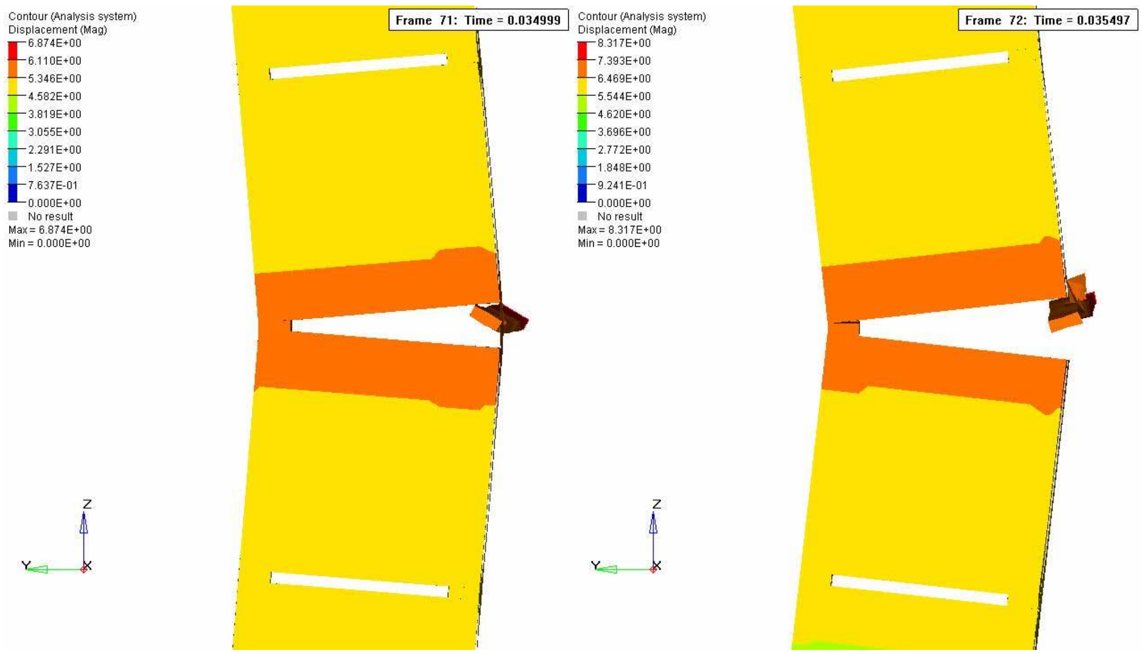


Figure 12. Wall Midpoint Maximum Displacements for Test 1.



Arching Model **No Arching Model**

Figure 13. Wall Deflected Shape for Test 1.



Arching Model **No Arching Model**

Figure 14. Mid-point Crack Details for Test 1.

For Test 2, the intentional selection of a large charge size caused the complete collapse of the membrane retrofit wall during the test. Finite element analysis of the arching and no-arching cases produced the same results for Test 2.

For Test 3, only the wall with membrane retrofit on the inside face of the wall was examined. The membrane retrofit thickness was increased to 0.25 inch accordingly, and analyses were performed for the no-gap and gap boundary condition, respectively. Figure 15 showed significant arching forces for the no-gap model, and zero arching forces for the model with gap.

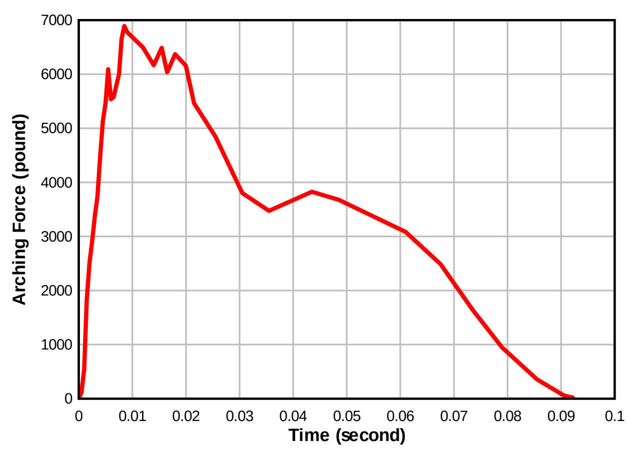


Figure 15. Arching Forces for Test 3.

The no-gap (arching) case showed a maximum displacement of 8.68 inches at the midpoint of the wall, versus the gap (no-arching) case that failed (Fig. 16). Figure 17 shows the deformed shape of the wall in for the model with no-gap and the model with gap. The model failure is distinct in the close-up view of the cracked section of the wall midpoint (Fig. 18). The gap model (Fig. 18, right) shows clear separation between the top and bottom halves of the wall. The maximum displacement results for Test 3 are within 7.5% of the test results of 9.38 inches.

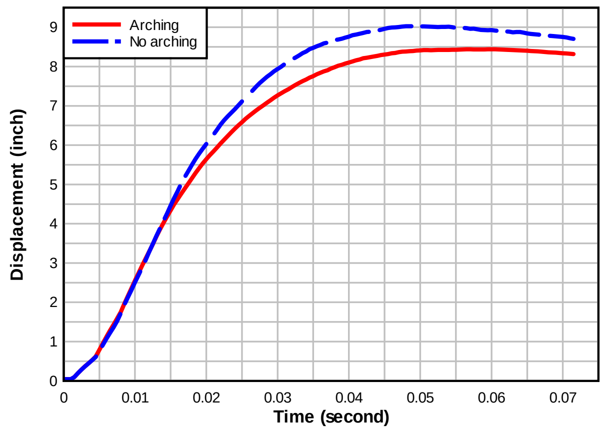
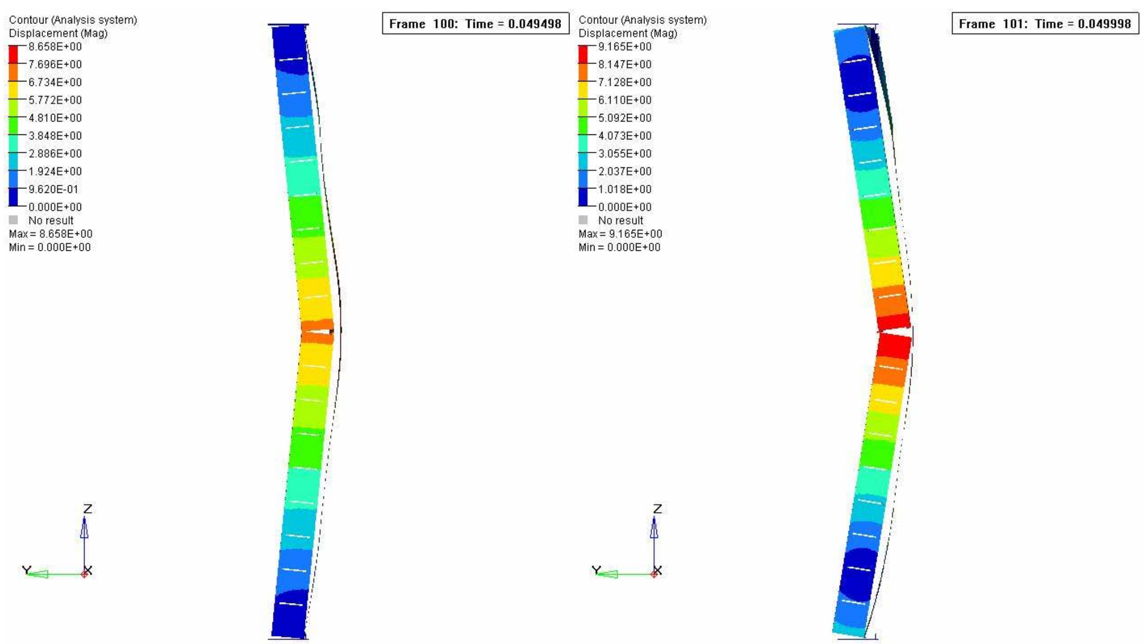


Figure 16. Wall Midpoint Maximum Displacements for Test 3.



Arching Model **No Arching Model**

Figure 17. Wall Deflected Shape for Test 3.

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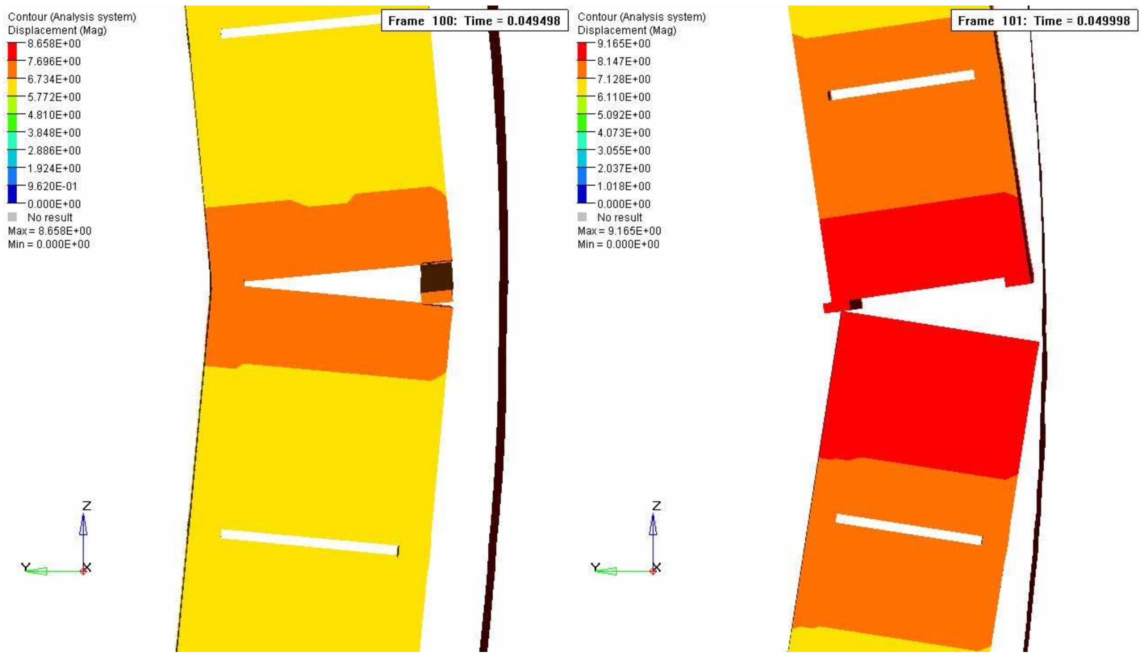

Arching Model **No Arching Model**

Figure 18. Mid-point Crack Details for Test 3.

In Test 4, the membrane retrofit is not attached to the concrete masonry wall and acts as a catcher system. The thickness of the membrane retrofit was changed to 0.12 inch, its material properties were properly described, and the contact forces between it and the concrete masonry elements were removed to simulate the unbonded conditions. Results showed significant differences in which the no-gap (arching) case showed a maximum displacement of 7.65 inches at the midpoint of the wall, versus the gap (no-arching) case that failed. The maximum displacement predicted by FE model for Test 4 are within 21% of the test results of 9.71 inches.

In Test 5, only the wall with the 0.25-inch membrane retrofit was analyzed, since the material properties of this retrofit were available. Results showed significant differences in which the no-gap (arching) case showed a maximum displacement of 6.21 inches at the midpoint of the wall, versus the gap (no-arching) case that failed. The maximum displacement results for Test 5 are within 26% of the test results of 8.36 inches.

In Test 6, two walls with identical construction and membrane retrofits were tested. One wall showed a maximum midpoint displacement of 9.7 inches during the test, while the second wall showed a maximum displacement of 11.5 inches. The results showed significant differences. The no-gap (arching) case showed a maximum displacement of 6.52 inches at the midpoint of the wall, versus the gap (no-arching) case that failed. The analyses maximum displacement results for Test 6 are within 33% of the test results for one wall and 43% for the other wall.

In Test 7, the membrane retrofit is not attached to the concrete masonry wall and acts as a catcher system (similar to Test 4). The contact forces between the membrane retrofit and the concrete masonry elements were removed to simulate the unbonded conditions. Results showed significant differences in which the no-gap (arching) case showed a maximum displacement of

7.73 inches at the midpoint of the wall, versus the gap (no-arching) case that failed. The maximum displacement results for Test 7 are within 40% of the test results of 12.9 inches. Table 2 summarizes the results from the finite element analysis.

Table 2. Comparison of test and finite element analysis results

Wall Test	**Retrofit thickness (in)**	**Height (ft)**	**Width (ft)**	**Test Max. Defl. (in)**	**FE Analysis Max. Defl. (in)**	**% Diff. with test**
1	1/8	12	7.5	7.2	No arching: Failed Arching: 6.9	4.2
2	1/8	12	7.5	Failed	Failed	---
3	1/4	12	7.5	9.38	No arching: Failed Arching: 8.68	--- 7.5
4	1/8 (not bonded)	12	8	Not available Survived	No arching: Failed Arching: 7.65	---
5	1/4	12	8	7.7	No arching: Failed Arching: 6.2	--- 19.5
6	1/8	12	8	11.6	No arching: Failed Arching: 6.5	--- 43.9
7	1/8 (not bonded)	12	8	12.9	No arching: Failed Arching: 7.7	--- 40.3

6.0 DISCUSSION AND CONCLUSION

The tests conducted by AFRL were designed to examine the effectiveness of polymer retrofits in mitigating wall disintegration and instability due to blast pressure. These tests were not designed to verify computational analytical models. The small number of tests shown in Table 2 does not lend itself to scientific statistical averages and makes it difficult to use them in verification of computational models. Running a large enough number of full-scale blast tests for dependable scientific averages is cost prohibitive. However, the availability of such data provides an opportunity for comparison and perhaps a tuning of the computational models for better results.

The test results include several areas of interest. In several of the tests, the maximum wall displacement at the midpoint was greater than the wall thickness of 7.625 inches. In two cases, the wall collapsed. A concrete masonry wall will collapse if the midpoint lateral displacement is greater than the wall thickness. In the other cases shown in Table 2 where the wall survived, the credit is attributed to the membrane retrofit. In most of these cases, the wall is no longer structurally sound but the membrane retrofit continues to hold it in place. This is one of the benefits that membrane retrofits provide toward prevention of the complete collapse of these walls.

Several of the wall tests have almost exactly the same geometry, charge size, and stand-off distance. The only difference is the type of polymer used in the tests. One example of this kind is the case of the Test 6 where the left wall displacement at the mid-point is 9.7 inches, versus the right wall midpoint displacement of 11.5 inches. In this test, the walls were built side by side in the same reaction structure. Another observation regarding Test 6 is that both walls experienced some level of collapse, and their final displaced shape points towards the blast source rather than caving into the occupied area.

The Test 7 results differed from the other tests discussed in this report. In this test a simulated vehicle search area was set up that included two walls, one of which had a retrofit over a common CMU wall construction (catcher system). The test included multiple barriers around the vehicle to replicate the damage incurred by the structures and barriers due to the pressure and fragmentation from explosives concealed in a vehicle. The wall deflected excessively but survived the test. The placement of the explosive charge in the vehicle and the barriers set up around the vehicle significantly alters the blast pressure experienced by the polymer retrofit CMU wall. This may potentially be the contributor to the differences between the maximum test displacement and those computed by analytical models shown in Table 2.

Although polymer membrane retrofits improve the structural stability of concrete masonry walls exposed to lateral blast pressure, they do not have a significant impact on the stiffness of these walls. Every polymer retrofit used in the tests had a low modulus of elasticity and tensile strength; therefore, the discrepancies noted in the tests were most likely not caused by the use of different polymers. They may be attributed to several other factors. The charge size and stand-off distance do not always generate the same blast pressure and impulse, as shown by Connell (2002) and Thornburg (2004). This is influenced by the size of the blast source, which is not always an exact measurement, the ground conditions underneath the blast source, which may not be the same from one test to another, and finally blockage by buildings, heavy concrete

partitions, temperature, humidity, or other items. The method of construction for concrete masonry walls varies from one builder and site to another. As much as these methods may be kept similar, differences creep in regarding material properties of the CMUs, mortar, outside temperature and humidity at the time of construction, the size of the gap at the top interface of the wall, etc.

The blast loads used in the finite element analysis were generated using the SBEDS program. The time versus pressure curve generated in this fashion is at best a good approximation, but does not match the pressure time history measured during the actual tests. This fact is shown in Fig. 10 for Test 1, and should be considered as one of the factors that influence the discrepancy between FE analysis and test results. The best approach is to digitize the test pressure time history for use in the analytical efforts; however, this is often cost prohibitive.

The finite element analysis results generally agreed well with results for Tests 1 through 5. The finite element method uses formulas, blast pressure, wall stiffness, and other parameters to compute the response. These parameters remain exactly the same from one model to another unless dictated by wall geometry, material properties, and or loading conditions. The same is not true for actual blast tests of membrane retrofit concrete masonry walls. The attempt to validate analytical results using actual wall tests that differ one from another based on factors other than the parameters used in the analysis may not be prudent in every case. It is certain to assume the success rate of the analytical methods would increase if tests could be performed in perfect conditions such that two identical walls would produce identical results under the same exact loading conditions.

In summary, this research provides a reliable high-fidelity finite element model to be used for detailed analysis of such walls where localized deformations, high-stress areas, and a host of pertinent parameters may be examined.

7.0 RECOMMENDATIONS

Based on the results of this research, the following recommendations are made:

1. Masonry walls should be constructed without any gaps at the top and bottom supports in order to develop arching forces.
2. The analyses indicate that metal membrane retrofits such as steel and aluminum sheets may be better choices for the retrofit of masonry walls as they are expected to increase the resistance of concrete masonry walls to lateral pressure. Future phases of full scale explosion testing should consider metal membrane retrofit techniques.
3. The analyses also indicate that other high stiffness, high-strength polymers may work better than the polyurea blends tested thus far. However, connection forces may increase dramatically and should be carefully considered.
4. Care must be given to the attachment of membrane retrofits to the wall, floor, and ceiling in order to fully develop the strength of the wall system.

Although membrane retrofit concrete masonry walls have shown great results in seismic and blast tests, further studies are recommended to quantify the improvement of this system for wind conditions, as well as tests to verify the analysis results. The studies should concentrate on:

a. The application of polymer retrofit materials to concrete masonry walls. To date, there is no objective evidence that polymer retrofits lack adequate adherence to the surface of concrete masonry. However, little research has been conducted to accurately determine the adherence of polymers to concrete masonry surfaces.

b. Application of the membrane retrofit material to the bottom and top boundaries of the wall needs to be investigated. Adequate extension and attachment of the membrane retrofit through the top and bottom supports play a major role in the structural integrity of the wall system.

c. Shock tunnel and static flexural tests of full-size or scaled membrane retrofit walls will allow for better instrumentation of the wall and membrane retrofit. The results will be used to fine-tune the current analytical models.

d. Static and dynamic tests to better define the strain for the arching ends. To date, little is published in the literature on the behavior of the arching ends of the wall system. Knowledge of the crushing behavior of the arched end while the wall experiences large deflections is important to the accuracy of the current analytical models.

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